A FUZZY LOGIC AUTOPILOT DEVELOPMENT FOR A LIGHT TWIN ENGINE AIRCRAFT IN THE APPROACH FLIGHT CONDITION

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Abstract

Purpose of this work is the development of a fuzzy logic based autopilot for a light twin engine aircraft. The aircraft considered for this application is a Piper PA-30 B Turbo "Twin Comanche".
The aircraft dynamic model is based on the complete equations of motion in a body-fixed frame and the aerodynamic coefficients are obtained from look-up tables.
The autopilot utilizes a series of waypoints to define the aircraft track. The aircraft attitude and configuration between two waypoints is kept constant.
The autopilot is tested during an ILS based final approach, one of the most critical flight conditions, and the results obtained confirm the feasibility of this autopilot system.

1 Introduction

At the Forlì Aerospace Engineering Department several studies are being carried out on the UAVs, to be used in civilian applications, just like fire detection.
One of these aircraft has already undergone flight tests, controlled by a remote operator, and now a flight control system is under development, in order to perform completely automatic missions. This control system consists of a ground station and an autopilot to be implemented on the onboard flight computer.
In the UAV design unconventional configurations are employed (twin boom configuration, pusher propeller, blended body, etc.). For these aircraft the aerodynamic and stability derivatives evaluation is very difficult and reliable data can be obtained only from expensive experimental measurements (wind tunnel investigations, flight tests), while from cheaper CFD analysis only approximated values can be achieved.
Controllers based on logic of indetermination do not enter in competition with the traditional ones, but can be complementary. They are suitable to control highly non linear systems, whose analytic model is difficult to be defined [1,2].
Using a fuzzy logic based approach even an aircraft can be controlled, whose mathematical model is not well defined in terms of aerodynamics and stability coefficients.
To verify the suitability of this kind of controllers, an autopilot for a Piper PA-30 "Twin Comanche" has been designed because many data on this aircraft were available and then it has been possible to carry out flight simulations.
The results obtained from several flight simulations demonstrate the capability of this autopilot to control the aircraft during an ILS based final approach flight condition, until the flare manoeuvre.

2 Simulation environment

2.1 Simulator

The autopilot has been tested on a flight simulator developed at the University Laboratories [3, 4].
To realize this simulator, whose structure is represented in figure 1, a cluster of Personal

Computers has been used in order to improve the processing power with relative low hardware costs.
The cluster is composed by a s erver, managing signal acquisition and data transfer in the net, and three client computers, two for the user interface (instrument panel and visual system) and one for the Instructor station.
To realize a synchronization in the signal transfer a TCP/IP protocol is used.

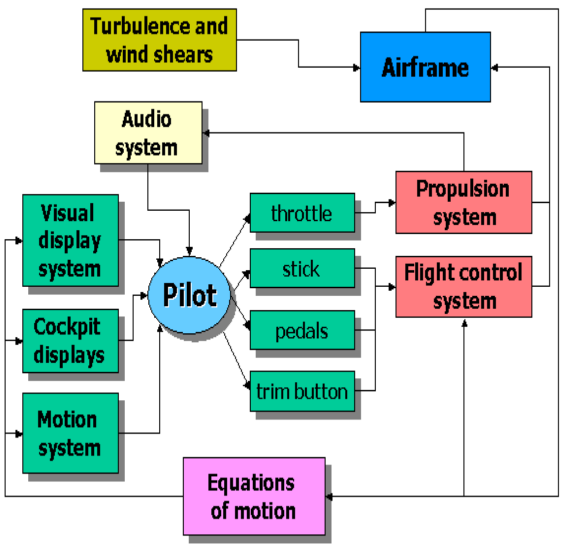

Figure 1 Flight simulator structure.

The instrument panel consists of a virtual cockpit equipped with several navigation instruments (air speed indicator, gyro horizon, ball-bank indicator, altimeter, vertical speed indicator, magnetic compass).
All the instruments have been realized with the LabVIEW software, both for the mathematical modelization and for the "on the screen" representation.
LabVIEW capability to be integrated with ad hoc C++ programs is used to control the signal transfer from user inputs to server PC and to exchange data from the server to the virtual instruments panel and the visual system.
The user interface is provided with a 4 axes joystick: the three classical flight controls (elevator, ailerons and rudder) and the engine throttle.

2.2 Aircraft dynamic model

The aircraft dynamic model is made up by the general force and moment equations for a rigid body in a body-fixed reference frame: the equations of motion are non-linear and the longitudinal and the lateral-directional dynamics are coupled. To avoid singularity problems in the equations of motion system the Euler angles relations have been replaced with the quaternions equations [5]. The equations of motion solver is based on a predictive Adams-Bashford algorithm and it is implemented on the server with a C++ routine.

The aircraft considered for the application described in this work is a light twin engine aircraft (Piper PA-30 "Twin Comanche"), owned by the University.
The aircraft aerodynamic coefficients in the various flight conditions are obtained from look-up tables based on experimental data [6], enabling, in this way, the aerodynamic coefficients updating at each simulation step.
The control inputs considered are the control surfaces deflections (elevator, ailerons and rudder) and the manifold pressure value.

3 Instrumental Landing System (ILS)

The Instrumental Landing System (ILS) coverage has been reproduced modeling the glide slope (figure 2) and the localizer (figure 3) signal.
If γ_a is the correct descend angle, the glide slope signal (*GS*) can be represented with the following expression:

$$GS = \begin{cases} 0 & \gamma \le 0.45 \cdot \gamma_a \\ -1 & 0.45 \cdot \gamma_a \le \gamma \le 0.88 \cdot \gamma_a \\ \varepsilon_{GS} & 0.88 \cdot \gamma_a \le \gamma \le 1.12 \cdot \gamma_a \\ 1 & 1.12 \cdot \gamma_a \le \gamma \le 1.75 \cdot \gamma_a \\ 0 & \gamma \ge 1.75 \cdot \gamma_a \end{cases} \quad (1)$$

where γ is the angle between the horizontal plane and the flight path (positive for the descend) and ε_{GS} is the error related to the difference between the aircraft actual flight path and the ideal descend path:

$$\varepsilon_{GS} = \frac{|\gamma - \gamma_a|}{0.12 \cdot \gamma_a} \qquad (2)$$

In this application a glide slope angle (γ_a) of 3° has been assumed.

The localizer is located along the runway centreline and generates a beacon, symmetrically respect to the runway centreline, whose angular width is 20° ($2 \cdot \xi_2$).

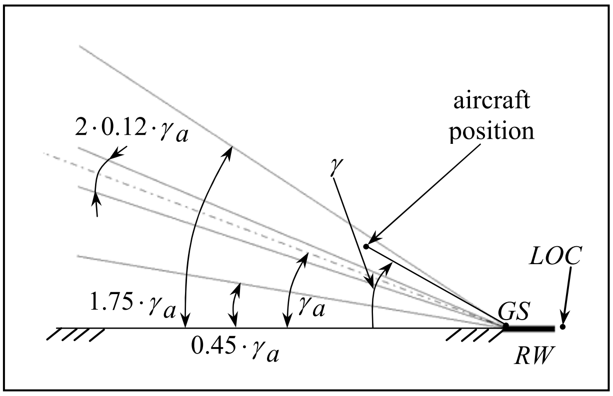

Figure 2 Glide Slope coverage.

The localizer signal (*LOC*) is variable only in an angular sector ($2 \cdot \xi_1$), whose intersection with the line through the approaching runway threshold measures 210 m [7]. For the runway considered in this application $2 \cdot \xi_1$ is about 4°.

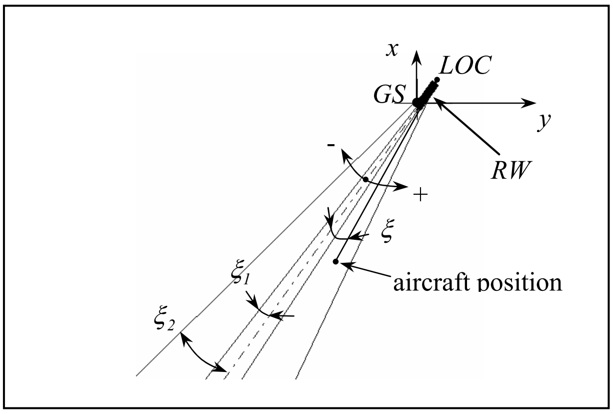

Figure 3 Localizer coverage.

The localizer signal has the following expression:

$$LOC = \begin{cases} 0 & \xi < -\xi_2 \\ -1 & -\xi_2 \le \xi \le -\xi_1 \\ \xi/\xi_1 & -\xi_1 \le \xi \le \xi_1 \\ 1 & \xi_1 \le \xi \le \xi_2 \\ 0 & \xi > \xi_2 \end{cases} \qquad (3)$$

It is possible to simulate the approach to any airport, fixing the latitude, the longitude and the altitude of the following points:

- the middle points of the two runway thresholds;
- the glide slope position;
- the localizer position.

4 Autopilot

The autopilot here developed is designed to follow a user specified path and to carry out a final approach to a runway provided with an ILS system, until the flare manoeuvre.
The flight path to be followed is defined fixing some waypoints. The flight condition between two waypoints is defined assigning to each waypoint a flight profile, named "flag", which is kept constant until the next waypoint.
The flight profiles used in this application are the "cruise" flag and the "ILS" flag: with the former height, heading and aircraft angle of attack have been kept constant, with the second the aircraft is forced to follow the ILS path.
The waypoints coordinates (latitude, longitude and altitude), together with the number of the associated flag, and the flight conditions typical of each flag are defined at simulation start.
It is also possible to change the flight path during the mission.

4.1 Autopilot structure

To carry out properly the landing manoeuvre, the aircraft must be on the ILS path during the final approach, with the nose aligned with the runway centreline, at a proper flight speed: this implies that the autopilot must evaluate the difference between the desired and the actual aircraft position and attitude. To this aim it is evaluated:

- the position errors, both vertical and lateral, based on the ILS signal;
- the heading error, obtained comparing the actual aircraft heading with that required to point towards the localizer (this correction is evaluated at each simulation step).

To simplify the autopilot structure, its scheme is based on dynamic decoupling.
The longitudinal regulator is composed by an altitude and vertical speed controller and by an attitude controller. The former acts on the throttle, using the manifold pressure as control input; the second acts on the elevator and, depending on the flight profile considered, controls the pitch angle (climb and loiter flight profile), the angle of attack (cruise and landing flight profile) or the climb angle (takeoff and descend flight profile).
Also the lateral controller has two control systems: a regulator acting on the ailerons, to control the roll angle and the heading, and a yaw-damper, acting on the rudder to cancel the lateral accelerations effects.
During the final approach fligh condition (flag = ILS), a variable gains method has been implemented to optimize the autopilot control.
For the head holder a look-up table has been created, assigning a gain value depending on the lateral position error and on the distance from the runway threshold: this gain multiply the aileron deflection value derived by the main controller.
For the longitudinal controller both the altitude holder and the attitude controller are been integrated by the application of gains, whose values depend only on the flight profile considered. In the altitude holder even the throttle mean value depends on the flight condition and the values obtained from the fuzzy controller represent only the deviation from the mean value.
The control system fuzzy rules have been fixed in order to avoid coupling of the actions on the control inputs, therefore a conflict management system is unnecessary.

4.2 Fuzzy code

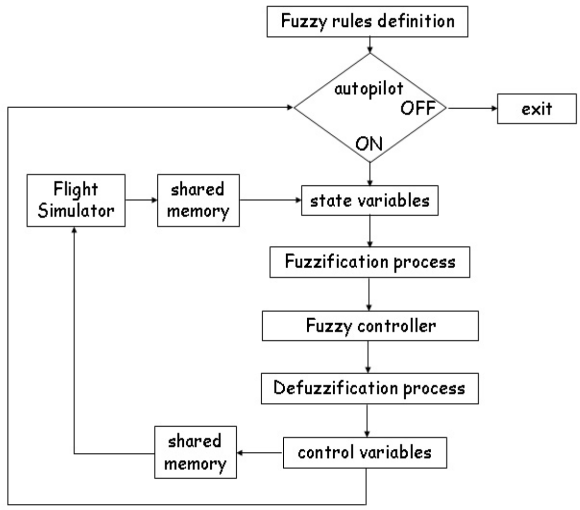

Figure 4 Fuzzy controller scheme.

The autopilot has been developed based on a Mamdani fuzzy inference system [1].
The input variables fuzzification is obtained applying triangular or trapezoidal membership functions, whereas the output variables defuzzification phase is based on the centroid method.
In this work fuzzy rules are employed with one or two inputs, as indicated by the following examples:

- one input rule:

IF "heading.goleft" THEN "aileron.goleft"

- two inputs rule:

IF "alt.down" AND "vario.down" THEN "throttle.fullfull"

The membership functions and the fuzzy rules, whose typology is indicated in the following tables, are defined in a text file, which is read at simulation start.

Table 1 Lateral controller: head holder.

	name	membership functions	
		number	type
Input variables	roll	2	trapezoidal
	head	2	trapezoidal
Output variables	ailerons deflection	2	trapezoidal

Table 2 Lateral controller: autorudder.

	name	membership functions	
		number	type
Input variables	lateral acceleration	3	triangular
Output variables	rudder deflection	3	triangular

Table 3 Longitudinal controller: altitude holder.

	name	membership functions	
		number	type
Input variables	altitude	3	triangular
	vertical speed	3	triangular
Output variables	throttle	5	triangular

Table 4 Longitudinal controller: attitude controller.

	name	membership functions	
		number	type
Input variables	flight condition	7	trapezoidal
	flight speed	3	triangular
	climb angle	3	triangular
	pitch angle	3	triangular
	angle of attack	3	triangular
Output variables	elevator deflections	3	triangular

Table 5 Fuzzy rules arrangement.

		number of fuzzy rules
Longitudinal controller	Altitude holder	9
	Attitude controller	21
Lateral controller	Head holder	3
	Autorudder	3

To improve the response velocity of the control system, whose action must be as quick as possible, the fuzzy software has been realized in C++, and in figure 4 the flowchart of the sofware is reported.

5 Autopilot test

To carry out the test of the fuzzy autopilot described in this work, a typical flight phases sequence has been defined:

1. manual takeoff
2. autopilot engagement
3. flight on the waypoints based path
4. ILS capture
5. final approach on the ILS path, until the flare phase
6. autopilot disengagement
7. manual landing and stop

The autopilot behaviour has been analyzed with different flight paths, with different aircraft positions and attitude at time of ILS capture.
Several test cases have been carried out in order to validate the autopilot. Following, two main cases are reported, different for the aircraft position with respect to the localizer mean plane at the ILS signal capture:

- case I: a runway approach from the left side
- case II: a runway approach from the right side

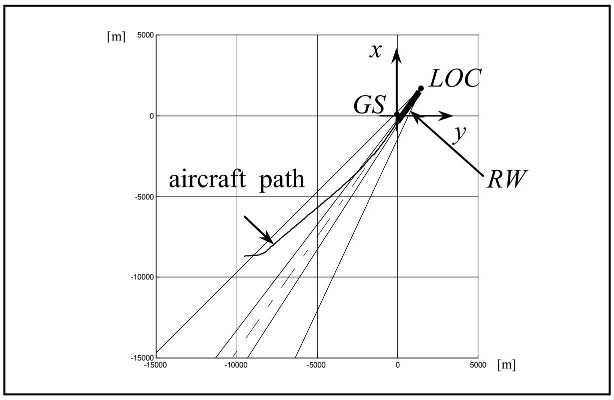

Figure 5 Case I: top view.

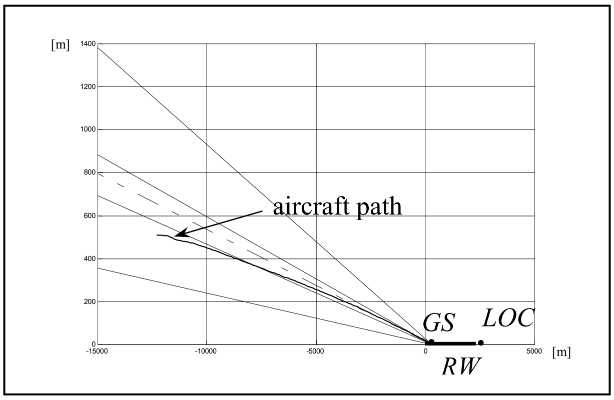

Figure 6 Case I: side view.

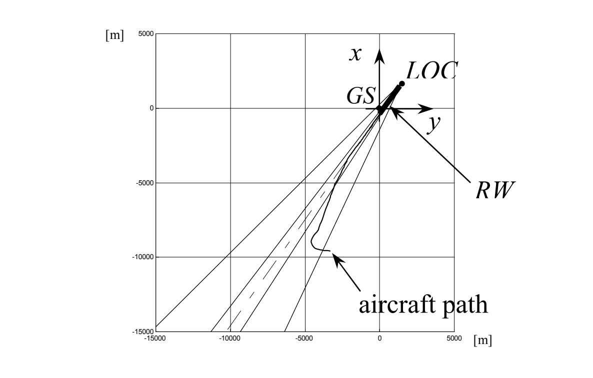

Figure 7 Case II: top view.

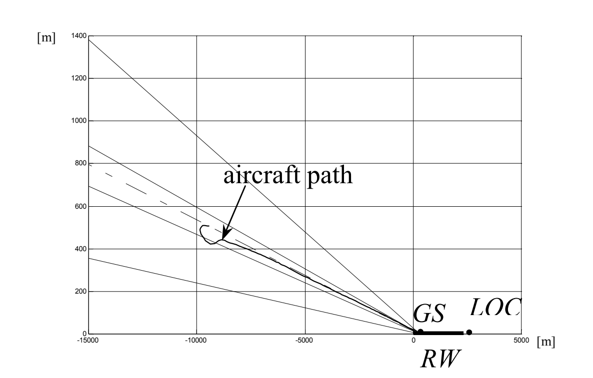

Figure 8 Case II: side view.

In both the cases the glide slope signal has been intercepted from the bottom, because this is the usual procedure to be followed, in order to avoid the 'false' glide paths, which have a slope of $n \cdot \gamma_a$ (*n* positive integer).

The figures (from 5 to 8) show that the aircraft follows the ILS path with a quite uniform trajectory.

The numerical results show that the aircraft can be controlled by the autopilot until to an height of about 11 m, relative to the runway. Under this height the control system is unable to maintain the aircraft on the ILS path and therefore it must be disengaged. The disengagement is just before the flare manoeuvre and the last portion of the landing must be carried by the pilot.

In any case the height reached by the aircraft under the autopilot control is enough to allow a full automatic approach to a runway equipped with a Category II ILS.

6 Conclusions

In this work the feasibility of a fuzzy logic based autopilot has been analyzed.

The aircraft considered in this application is a light twin engine aircraft, whose aerodynamic characteristics are known from experimental analysis, so it has been possible to carry out flight simulations.

The tests have been focused on the ILS based final approach flight condition and the results obtained demonstrate the autopilot capability to control the aircraft until the flare manoeuvre.

In the next future this autopilot will be improved in order to automate the entire landing phase and aircraft stop. In this way the flight manage system will be complete and it will be possible to realize an entire mission profile with a full automatic control system.

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